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TERRACE PEDIMENTS IN MAKHTESH RAMON, CENTRAL NEGEV, ISRAEL

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ABSTRACT

Terrace pediments occupy approximately 30 per cent of the bottom of the Makhtesh Ramon erosional cirque in the central Negev Desert, Israel. River terraces and terrace pediments are genetically connected landforms, where each terrace pediment corresponds with a fluvial terrace of the same relative height. A pediment and river terrace constitute a geomorphic pair and should be regarded as chronometrically synchronous morphological elements. The formation of the terrace pediment staircases is controlled mainly by local base level changes. The present-day configuration and overall morphology of Makhtesh Ramon formed in the early stages of its development by both stream erosion and subsequent pedimentation. Less significantly, modification by intermittent erosion alternating with periods of stability, resulted in deepening of the Makhtesh Ramon bottom. The present-day stepped relief throughout the Makhtesh valley is, thus, a composite feature. The overall rate of terrace pediment formation in Makhtesh Ramon ranges from 0·05 to 0·10 mm a^{-1}. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: terrace pediment; base level; staircases; rock varnish; luminescence dating; Israel

INTRODUCTION

Wide terrace-like features occur along the perimeter of Makhtesh Ramon erosional ‘cirque’ in the central Negev desert of Israel. These terrace pediments constitute one of the principal elements of the Makhtesh Ramon bottom topography. Terrace pediments are constrained by a major base level (Cooke *et al.*, 1993), and they generally develop on soft sedimentary rocks (Howard, 1942; Mammerickx, 1964; Royse and Barsch, 1971). They are often, as is the case in Makhtesh Ramon, covered by a veneer of weathered rock (Twidale, 1981). Terrace pediments are locally significant arid landforms because they represent a transition of a sloping surface between an upland watershed and a base level area (Cooke *et al.*, 1993). Thus, they are often considered elements of both slope and alluvial plain systems. In contrast with Denny (1967), we consider pediments as more than an erosion surface on bedrock, but rather as a key landform, reflecting both an erosion stage and a stage of stability. As a rule, when a pediment has reached a stage of stability its sedimentary cover experiences a variety of physical and chemical processes that reflect both the maturity (age) of the pediment surface and climatic changes.

The origin of pediment staircases is generally viewed in a cyclical perspective. The changing of system conditions results in a sequence of landforms of different age (Schmidt, 1992). Pediments have been recognized within stratigraphic columns (Williams, 1967), with each component of the pediment staircases occupying a distinct morphostratigraphic position.

Terrace pediments are fundamentally of erosional forms. Terrace pediments and alluvial terraces are morphologically similar landforms, and often the thickness of their sedimentary cover in Makhtesh Ramon is

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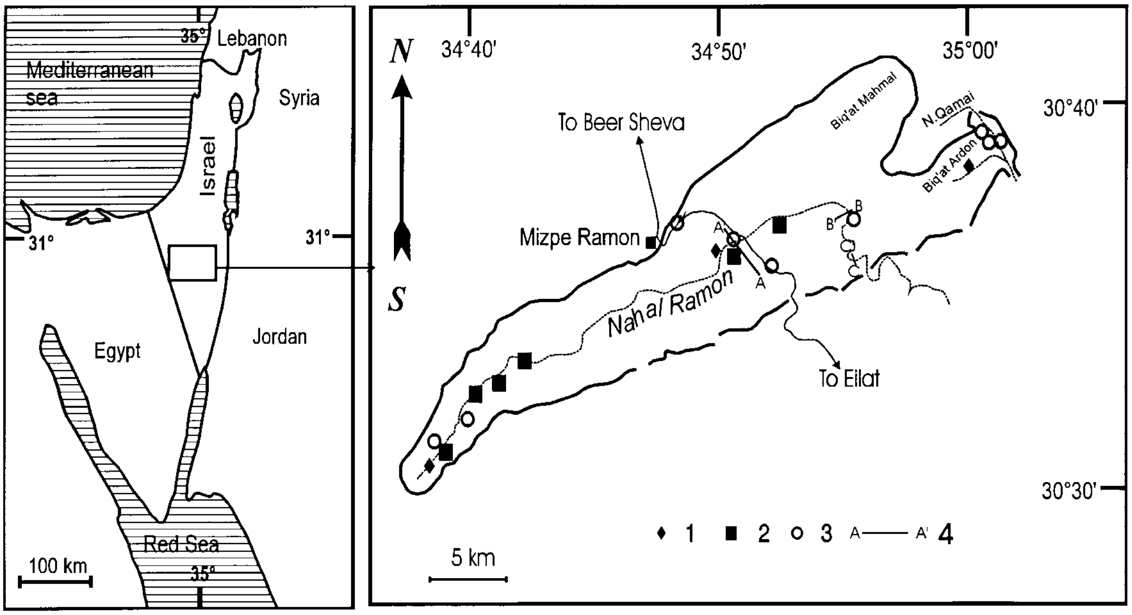

Figure 1. Location map of Makhtesh Ramon. Key: 1, modern pollen samples; 2, pollen samples from the terrace sections; 3, RTL samples; 4, geomorphological cross-section

almost the same. Hence, the problem arises as to the definition of the genesis of these two piedmont landforms for their identification and mapping.

The aims of the present work are to (1) characterize the morphostratigraphy of pediments in Makhtesh Ramon, (2) define the relations (synchronous or asynchronous) between fluvial terraces and pediment terrace staircases as a means of correlating time-equivalent systems in Makhtesh Ramon, (3) evaluate the main factors controlling the development of the morphological systems, and (4) attempt to calculate the rate of pediment formation.

Makhtesh Ramon can serve as a natural model for a more general understanding of pediments because (i) of the relatively homogeneous lithological composition of the underlying rock over the entire valley, and (ii) the makhtesh is drained by a single drainage system.

STUDY AREA

Makhtesh Ramon is a deep erosional 'cirque' 40 km long and 12 km wide entrenched along an anticline axis and surrounded by steep walls (Figure 1). Its area is 241 km^2. Altitudes range from 1020 m on the western rim to 420 m a.s.l. near the outlet of the main wadi, Nahal Ramon. This ephemeral stream is 39 km long within the makhtesh, and drains most of it. Nahal Neqarot, which flows east of the Ramon anticline towards the Dead Sea, serves as the local erosional base level of the Ramon valley.

The climate of the area is arid to extremely arid. Mean annual rainfall is 85 mm at the northern rim and only 56 mm at the 'cirque' bed in the central part. Mean daily temperature in July is 34°C, and drops to 12·5°C in January; mean annual temperature is 17–19°C.

The lithological sequence exposed in Makhtesh Ramon ranges from Triassic to Cretaceous. Triassic rocks, which are about 500 m thick (Zak, 1963), are composed of carbonate, sulphate, shale and sandstone lithofacies. The Jurassic section, about 400 m thick (Nevo, 1963) is composed mainly of friable sandstones of Inmar Formation (Goldberg, 1970) with a subordinated representation of carbonate rocks, siltstones and clays. The Early Cretaceous Hatira Formation is divided into three members: the lower and upper members

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are composed of loose sandstones 5–40 m and 80–120 m thick, respectively. Sandstone members are separated by a basanite unit 100 m thick in the western part of Makhtesh Ramon (Eyal *et al.*, 1996), and 0–30 m in its central part. The cliffs surrounding the makhtesh are built of 300 m thick hard limestones and dolomites of the Middle Cretaceous Hazera Formation.

The Quaternary development of Makhtesh Ramon can be generalized as the alternation of periods of erosion and stability, caused by periodic lowering of base level. The first stage of base-level lowering began with erosional activity, associated with the deformation along the Dead Sea–Arava Rift Valley (Zilberman, 1991). Erosion destroyed the regional Oligocene erosion surface and exposed the Ramon anticline structure. The lower landforms are younger because of the higher topographic position of Makhtesh Ramon in relation to its base level in the Dead Sea basin. An interrupted incision of the Makhtesh Ramon drainage system occurred since the Pliocene (Ben-David *et al.*, 1992; Zilberman, 1991).

METHODS

The morphological systems of Makhtesh Ramon were studied during a geomorphological mapping project carried out at a scale of 1:50 000. The morphostratigraphy of stream terraces and terrace pediments was established and time-equivalent systems were correlated (Plakht, 1996).

The sedimentological character of alluvium, together with pollen and pedological data, aided correlations and environmental reconstructions. The alluvium deposited under an arid climate often consists of single, homogeneous units. Beds composed of coarse sediments alternate with beds of abundant fine clasts in the alluvium, sometimes with an abrupt change between beds of different texture characterizing more humid periods (Grossman and Gerson, 1987). A calcic pedogenic horizon usually develops when the effective humidity in the soil is equivalent to an annual precipitation above 200–250 mm, and it is leached when annual rainfall exceeds 450–500 mm (Bruins and Yaalon, 1979; Birkeland, 1984).

A total of 45 samples for pollen analysis were collected from the recent channel, floodplain and terraces of the Ramon valley; pollen analysis was performed by G. Kartashova in the Palynological Laboratory, Moscow State University. The sampling was done throughout the terrace sections. In coarse alluvium the samples were extracted from the matrix. An interpretation of the pollen data is based on an analysis of non-arboreal pollen (Horowitz, 1992). The gradual changes of climate from extremely arid to semi-arid were noted with the succession of dominant families: Chenopodiaceae → Cruciferae → Compositae → Umbelliferae (Plakht, 1995a).

The radiothermoluminescent (RTL) method was used to establish numerical ages. The RTL approach is based on dating the last exposure to light of sediment grains prior to burial (Wintle and Huntley, 1982; Aitken, 1985). Sixteen samples were collected from the alluvial terraces. Natural quartz was employed as a thermoluminescent palaeodosimeter. The RTL analysis was performed by O. Kulikov, Departments of Geography and Chemistry, Moscow State University, using a technique based on high-temperature elementary glow peaks. According to this technique '..the glow curve from quartz of a paleodetector irradiated additionally in laboratory conditions by the dose represents the superposition of a large number of elementary peaks and can be used for its calibration with prior treatment. Isothermal annealing at $T = 200°C$ for 20 min makes it possible to determine the age peak at $Tmax = 310°C$' (Vlasov and Kulikov, 1989, p. 554). The elementary peak can be verified by the method of ordinate relations (plateau test).

Arid and extremely arid climatic conditions in the Negev Highlands are favourable for the development of rock varnish covering up to 70 per cent of particles on different geomorphological surfaces. It was noted that the chemical composition of the varnish, mainly its manganese and iron contents, as well as the ratios between some elements (e.g. Fe/Mn, (K+Ca)/Ti, Fe/Ti) in the manganese-rich varnish (Mn concentration $> 0{\cdot}1$) can give calibrated and numerical ages of geomorphic surfaces if calibrated with other methods such as ^{14}C (Dorn, 1983, 1988; Dorn *et al.*, 1987, 1992; Harrington and Whitney, 1987). To use rock varnish as an age marker, the varnish composition of sandstone particles sampled from the different terraces and pediment surfaces was analysed.

The chemical composition of the varnish was studied using an X-ray spectral microprobe analyser (Camebax) with a dispersion X-ray spectrometer (Link 860-500) according to the program ZAF/PB. This

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special technique was developed by G. Nechelustov for unpolished surfaces, and was used because of the extreme thinness of patina. We conducted 67 analyses on chemical elements characterizing 15 samples from different geomorphic levels, including nine samples of the training group and six samples of the control group.

As shown previously (Patyk-Kara *et al.*, 1997; Gorelikova *et al.*, 1999), the relationship between rock varnish chemistry and geological age of geomorphic surfaces is very complicated, and this is confirmed by data of correlation analysis. In this connection the task of modelling this relation has been set, taking into account not only elemental concentrations, but their ratios and products. For revealing criteria characterizing samples from different levels, analytical data were studied using logic informative analysis developed by I. Chizhova (Gorelikova *et al.*, 1999). This method is based on the examination of variation of object ranges and the similarity concept. The essence of this algorithm is to distinguish indicator intervals from element concentrations, to describe test objects, and to estimate their significance for further identification of objects on the basis of dividing weights. When solving a recognition task, a commonly used idea is the property similarity concept, which is as follows: objects of the same class possess property similarity reflected in their characteristics. The use of this concept in building a recognition system allows some regularities typical to every class to be revealed. These regularities are used in the further procedure of variation range analysis.

For the description of the relationship between absolute age (Y) and concentration values of elements (X_1, X_2, aXn), a non-linear relation of the following form was used: $Y = \mathrm{F}(X_1, X_2, aXn)$, where Y is absolute age, and X_1, X_2, Xn are concentrations of elements. For the solution of this equation, a simplex method was used. The description of the desired model is the following:

$$Y = a_{00} + \sum_{i=1}^{N} a_{0i} + \sum_{\substack{i,j=1 \\ i \neq j}}^{N} (b_{ij}x_i x_j + c_{ij}x_i/x_j + d_{ij}x_i/x_j)$$

where $X = (X_1, X_2, \ldots Xn)$ is a description of a sample in a set of initial signs, that is, of the contents of chemical elements. The study of desired coefficients *a, b, c, d* is conducted based on the condition of minimization of $/Yk - Vk/-$ distinction between calculated values (Yk) and initial values (Vk), characterizing the age of a sample k. As a result of the analysis, the database for an expert system was constructed allowing dating of geomorphic levels on chemistry varnish coating. This model provides a reliability of dating equal to 0·8. The calculated value is considered as the generalized geochemical indicator (Gi_{rv}) of rock varnish dating. When solving for this equation, the main task is in the search for coefficients satisfying initial conditions. As a result, coefficient values *a, b, c, d*, which described a desired model for dating of geomorphic levels on rock varnish chemistry, were estimated. For calculating numerical ages, the absolute age scale was applied on the basis of thermoluminescence data by O. Kulikov. For verification of this model, control samples from Makhtesh Ramon were analysed and geological ages were calculated on the basis of the developed approach. The results obtained correspond to geological and thermoluminescent data (Patyk-Kara *et al.*, 1997; Gorelikova *et al.*, 1999).

FLUVIAL TERRACES IN MAKHTESH RAMON

Three main morphological systems occupy the bed of Makhtesh Ramon: modern stream channels, alluvial terraces and terrace pediments (Plakht, 1995b). A significant area (31 per cent) is occupied by bedrock exposures.

Fluvial landforms occupy 29 per cent of the bottom of Makhtesh (Figure 2); they consist of floodplain and six terraces (Figure 3). The relative heights of the terraces do not change along the valley. The floodplain (1·5–2 m above the channel) and terrace I (3–4 m) are composed mainly of horizontally bedded pebbles in a sandy matrix. Pollen spectra reflect a true desert flora similar to the modern floral composition in this region (Horowitz, 1979; Plakht, 1995a; Ward and Olsvig-Whittaker, 1993; Ward *et al.*, 1993).

About half of the section of terrace II (5–6 m) is composed of fine clastics. Calcic buried horizons with pedogenic carbonate nodules, together with pollen spectra in which steppe elements predominate,

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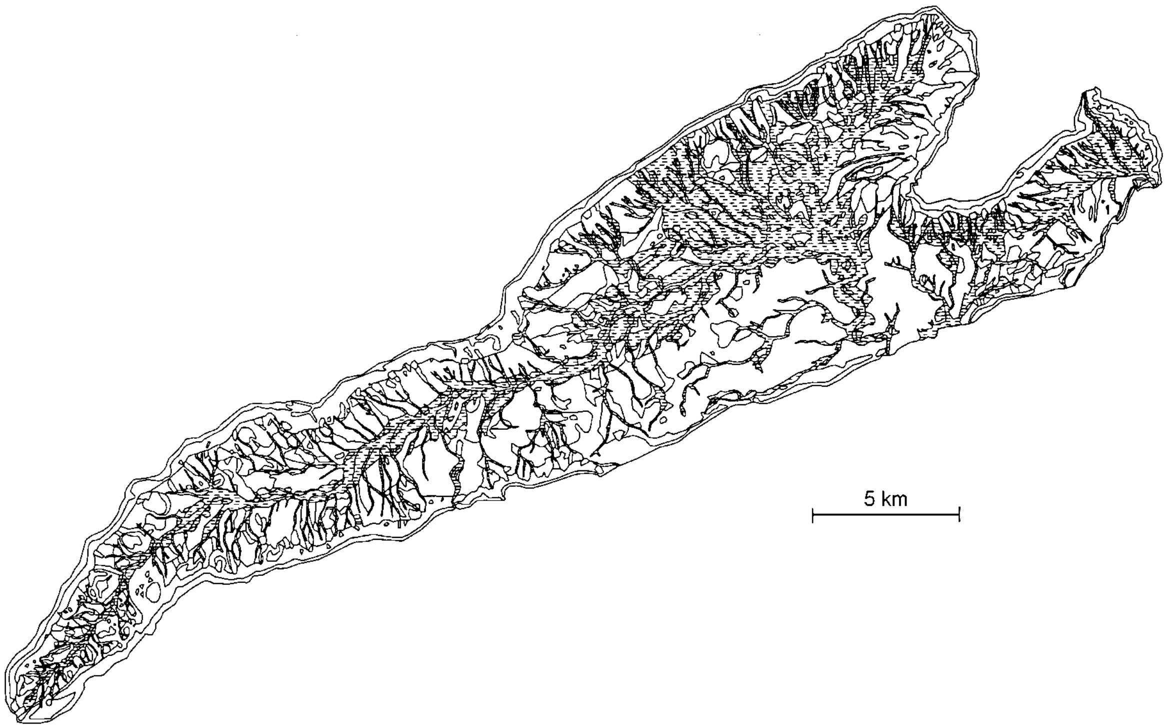

Figure 2. Fluvial landforms in Makhtesh Ramon: fluvial landforms are shown by horizontal dashed lines

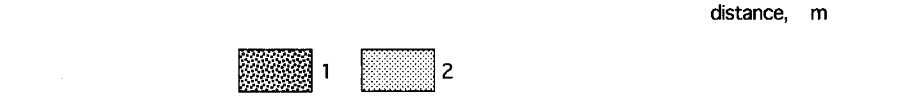

Figure 3. Geomorphological section across the middle reaches of Nahal Ramon indicating the main fluviatile elements. Key: 1, alluvium; 2, Bedrock

demonstrate a semi-arid climate with an annual rainfall exceeding 200 mm (Birkeland, 1984; Zilberman, 1992). The absolute age of buried calcic palaeosols in the middle of the terrace section according to the RTL method is 27 ± 7 ka. The alluvium of terrace IV (13·5–15 m) with similar composition and almost the same character of pollen spectra was dated as 150–100 ka (Figure 4).

The alluvial cap of terrace III (8–10 m) is mainly composed of pebbles in a sandy matrix. Pollen data reflect more arid conditions compared to terraces II and IV, which presumably occurred, according to RTL analysis, 55–40(?) ka.

The alluvium of the upper part of terrace V (18–20 m) and terrace VI (25–30 m) was deposited 205 ± 41 to 240 ± ka and 375 ± 95 to 443 ± 110 ka, respectively. Pollen data (Horowitz, 1979, 1992) show that most of

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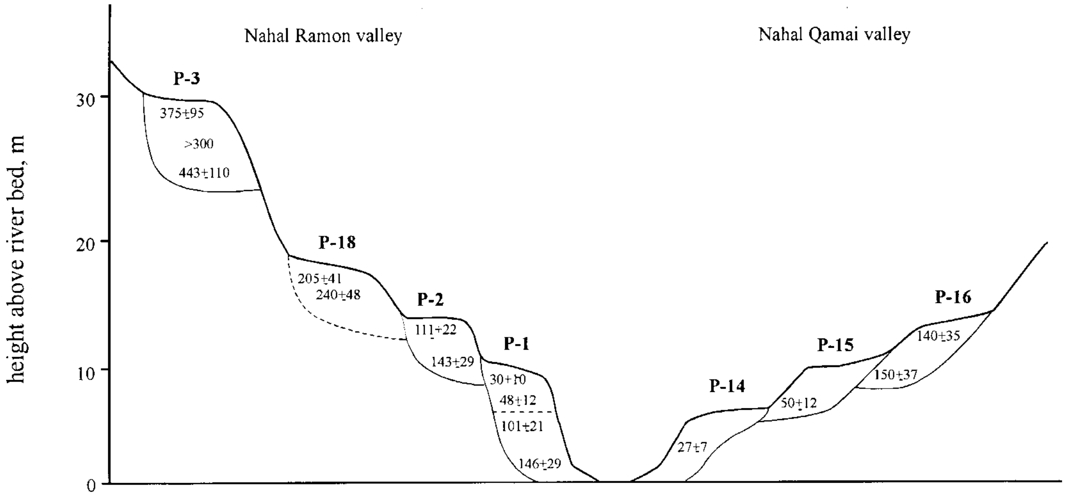

Figure 4. Radiothermoluminescent (RTL) data of the terrace alluvium

the interval 250–200 ka was characterized by desert conditions in southern Israel, whereas during the period 350–450 ka, relatively humid climatic conditions prevailed. Thus, the formation of alluvial terraces in Makhtesh Ramon probably occurred under different climatic conditions.

TERRACE PEDIMENTS IN MAKHTESH RAMON

Terrace pediments constitute one of the most widespread morphological components of Makhtesh Ramon. They occupy 23 per cent of the bottom of the basin (Figure 5), approximately the same area as the fluvial relief. Terrace pediments occupy 44 per cent of the western part of the Makhtesh, three times the area of fluvial landforms there. The pediments have almost level surfaces, their slopes increasing from $0{\cdot}5^0$ in the lower part to $6{\cdot}4^0$ in the upper part. They developed mainly on tilted Jurassic and Early Cretaceous loose sandstones.

Terrace pediments form a ‘geomorphological staircase’ along the perimeter of Makhtesh Ramon with heights of 3–4 and 5–6 m (lower surfaces), 8–10 m and 13·5–15 m (medium surfaces), and > 20 m (two higher pediment surfaces) above the present Nahal Ramon bed. Thus, exact correspondence between the heights of terrace pediments and fluvial terraces is clearly observed. Pediment surfaces are gullied to variable degrees.

As a rule, the thickness of the terrace pediment mantle does not exceed 1–3 m. On the medium and higher surfaces the upper thin (not more than 5–7 cm) horizon is enriched by coarse material reflecting the cyclical processes of physical (wetting and drying, insolation) and physical–chemical (salt) weathering (Goudie, 1985; Goudie *et al.*, 1970; Cooke, 1981). The morphological effect of these processes is the formation of desert pavement (hammada). Most of the bare particles are coated by rock varnish.

The particles in the terrace pediment mantle are almost angular, even on the distal parts of the pediment surfaces (mean values are 0·1–0·2 according to Krumbein (1941). At the same distance from the river head, the roundness coefficient of alluvial pebbles reaches 0·4–0·5. It is supposed to be a result of the different movement patterns of particles in a flow. Whereas particles in the river bed move by rolling, saltating and dragging because of the high velocity of the linear current, the process of dragging predominates on the pediment surface under the condition of a relatively slow, sheet-like current. As a result, particles which form a pediment cover have only a slightly rounded upper surface, whereas their lower surface is absolutely unrounded. Probably, weathering and especially wind erosion also play a significant role in the process of roundness of the upper surface of a particle. Such ‘rounded’ limestone blocks are very typical on the bare

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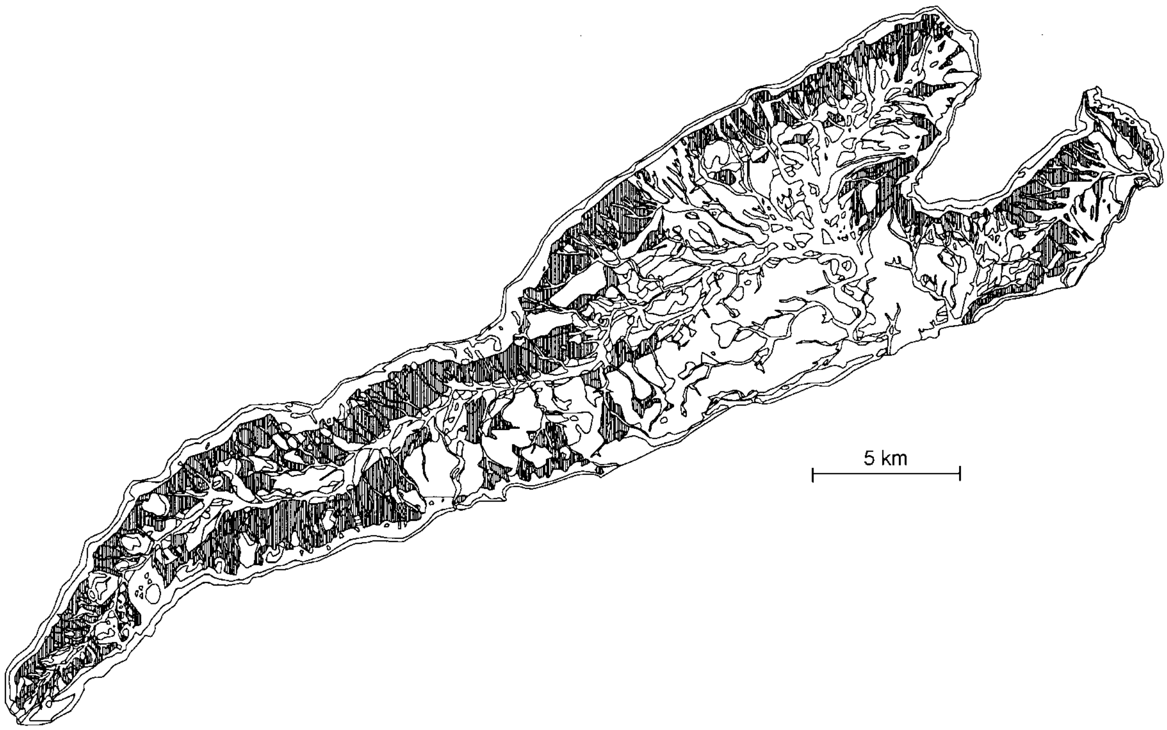

Figure 5. Terrace pediments in Makhtesh Ramon: pediments are shown by vertical shading

slopes. This feature, together with the analysis of the texture of sedimentary cover, helps us to define the origin of landforms.

The remnants of higher terrace pediments are preserved mainly near both the southern and northern slopes of the makhtesh. The most widespread 8–10 m pediment surface occupies 40–50 per cent of the entire pediment area. However, this does not mean that the process of pedimentation has taken place mainly in the period of the formation of this surface. Destruction by slope erosion and retreat has eliminated a significant part of the higher pediment belt.

DISCUSSION

The genesis of pediment staircases is widely discussed in the geomorphological literature. Most ideas relate to interrupted lowering of the regional (Mensching, 1973) or temporary (Warnke, 1969) base level. The changing of base level position in the context of the formation of the terrace pediment succession can depend on tectonic movements and their effect on the fluvial system (Tuan, 1962), on valley-side planation (Bryan, 1936), or on climatic alternations (Mabbutt, 1966). Cooke *et al.* (1993) claimed that all these factors could be involved in pediment sequence formation.

Royse and Barsch (1971), observing both fluvial terraces and terrace pediments within the same drainage basin, concluded that these two types of surfaces had different heights and did not grade into one another, and, therefore, they were non-synchronous landforms. Royse and Barsch (1971) suggested that terrace pediments were products of arid climatic episodes, whereas fluvial terraces were formed during more humid episodes.

Schmidt (1992) explained that rock-cut pediments are a product of a non-continuous erosion process due to resistant layers. Cooke *et al.* (1993) emphasized that '...the pediment may legitimately be considered as a

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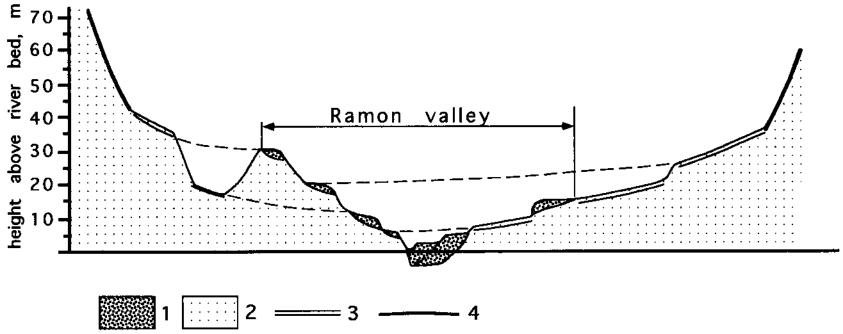

Figure 6. Cross-profile indicating the relation between river terraces and pediment terraces in the central part of Makhtesh Ramon. Horizontal dimension is schematic. Key 1, alluvium; 2, Bedrock; 3, pediment surface; 4, slope

functional component of a drainage basin' (p. 192), and, thus, it must be subordinated to changes of a drainage basin. A pediment simultaneously serves as a connecting link between a piedmont and a slope system, forming a common geomorphological system, whose development depends, all other factors being equal, on changes of local base level position. The reasons for such changes can be tectonic, climatic or hydrological.

Terrace pediments in Makhtesh Ramon are mainly developed on the Jurassic and Cretaceous non-resistant sandstones. The relatively homogeneous substrate and the single drainage system of Makhtesh Ramon provide an opportunity to define the main reasons for the formation of terrace pediment staircases, because the conditions of their development are almost equal all over the Makhtesh area.

Each pediment grades towards a river terrace at its base (Figure 6). Having the same relative heights as river terraces (the same morphostratigraphic position), the pediment belt is thus temporally related to the terrace sequences below. The terrace pediment and the related river terrace constitute a pair and should be regarded as synchronous morphological elements. Therefore, if some terraces were to be completely destroyed by erosion, it would be possible to reconstruct their previous position within staircases by extrapolation from the analysis of the pediment system.

The values of the generalized geochemical indicator of rock varnish (Gi_{rv}) change stepwise from one geomorphological level to another (both river terraces and pediments) corresponding to the changes of the RTL age of the terrace alluvium (Table I).

The data demonstrate that the age (Gi_{rv}) of a pediment surface in all cases is rather older than the age of the corresponding fluvial terrace (Table I, Figure 7). This cannot be accidental, and must reflect conditions of pediment formation.

We suppose that the explanation of this fact can be obtained from conditions of formation of both landforms. When examining the recent valley bottom, it can be observed that a pediment related to a

Table I. Generalized geochemical indicator of rock varnish (Gi_{rv}) at Makhtesh Ramon

Samples	Landforms	Number of measurements	Gi_{rv}(ka)	
			Range	Mean
RVT-9	Terrace, 25–30 m	5	362–404	381
RVP-20	Pediment, 25–30 m	8	430–458	441
RVT-18; 18K	Terrace, 18–20 m	9	232–257	246
RVP-1;4; 6/MR	Pediment, 18–20 m	12	229–273	253
RVT-16	Terrace, 13·5–15 m	5	93–106	101
RVT-18	Terrace, 8–10 m	4	31–60	45
RVP-3	Pediment, 8–10 m	3	55–72	61

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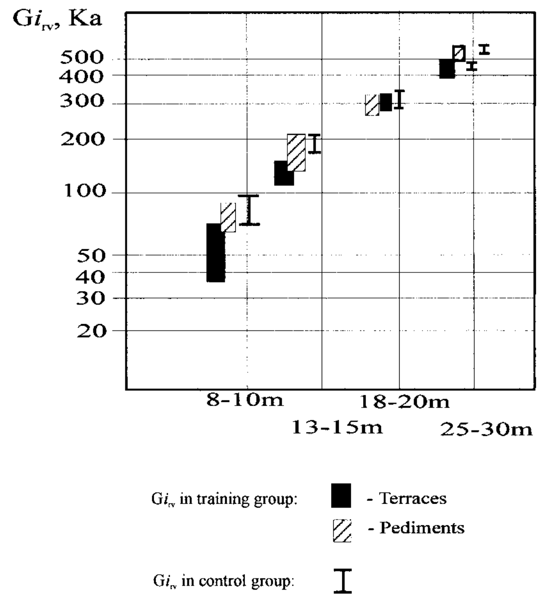

Figure 7. Values of the geochemical index Gi_{rv} for fluvial terrace and pediment levels showing the phenomenon that the pediments are older than the corresponding terraces

floodplain surface is an aerial landform, whereas a floodplain is subjected to recurrent flooding. This phenomenon is widely distributed in valleys of southeast Siberia (Timofeev, 1962). We also observed widespread 'bottom' pediments related to a floodplain and occupying up to 40–60 per cent of a recent valley bottom (Patyk-Kara, 1970). Thus, aerial processes, including various geochemical processes, act on a pediment surface, whereas the corresponding fluvial surface is still subjected to flooding. In other words, a pediment as an aerial surface is 'older' than a fluvial terrace of the same level. That may explain the observed distinction between their ages, calculated from geochemical data (rock varnish patina).

Although the development of rock varnish on fluvial surfaces lags behind such development on pediments, our data show a distinct temporal connection between these two types of landforms. These data suggest that: (i) the degree of maturity of geomorphic surfaces is different; and (ii) river terrace and terrace pediment of the same heights form a morphological pair within a single piedmont system.

The first erosional stage of the development of Makhtesh Ramon ended with a period of stability, during which the highest river terrace and pediment surfaces formed. The occurrence of the highest pediment remnants, mainly near the southern and northern walls, indicates that slope retreat since this stage has been minor, and that the width of Makhtesh Ramon has not changed significantly during the subsequent stages of development. Thus, each new and lower pediment surface was formed mainly as a result of the erosion of the higher pediment belt. The lowering of base level disturbs the equilibrium conditions and results in removing the pediment cover and the upper part of the bedrock. Erosion of the bedrock and pediment continues until a new equilibrium is established.

Proceeding from the absolute ages of the upper parts of alluvial cover of some terraces (and, correspondingly, of synchronous terrace pediments), and from the differences in their heights, we can estimate approximately the rate of pediment formation. The rate of pediment formation can be expressed by the equation $R = D/\Delta H$, where R is the rate of pediment formation, D is the duration of this process (sum of both erosional cycle and period of stability), and ΔH is the difference in heights of pediments.

The age of the upper part of terrace V (18–20 m) is approximately 200 ka. The development of the lower part of terrace IV (13–15 m) was completed in 100 ka. Thus, the terrace IV formation (erosion + accumulation) lasted about 100 ka. The difference in the terrace heights is 5 m. Thus, the rate of the formation of terrace IV was 0·05 mm a^{-1}.

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Almost the same supposed rate is suggested during terrace III (8–10 m) formation. The alluvium of terrace III began to deposit 55 ka ago, and finished approximately 40 ka BP. The duration of terrace III formation was 100 ka (final stage of terrace IV formation) − 40(?) ka = 60 ka; the difference in heights of terraces IV and III is 5·5 m. Thus, $R = 0{\cdot}10$ mm a^{-1}. For comparison, Dohrenwend *et al.* (1986) determined the erosion rates of downwasting on the surface of a pediment dome developed on basalt flows in the Cima volcanic field, Mojave Desert, California, to a range of between 0 and 0·04 mm a^{-1}. Thus, our estimates for Makhtesh Ramon are certainly within the same order of magnitude as displayed elsewhere.

CONCLUSIONS

1. The overall configuration of Makhtesh Ramon is largely a result of the early stages of both stream erosion and pedimentation. Modifications over the last approximately 0·5 Ma have been insignificant. Periods of erosion alternate with periods of stability, resulting in its deepening and the creation of stepped landforms on its bottom. The uppermost pediment and alluvial surfaces reflect the first period of stability.
2. River terraces and terrace pediments within the Ramon basin have close connections. Each pediment surface is linked to a terrace of the same relative height. The formation of terrace pediment staircases is similar to the formation of river terrace staircases, and depends on changes in local base level.
3. The chemistry of rock varnish, when analysed by linear programming, allows us to conduct absolute and relative dating of geomorphic surfaces of the central Negev region. This approach advances our understanding of the complex problem of dating of different geomorphic surfaces.
4. The rate of terrace pediment formation in Makhtesh Ramon is estimated as 0·05– 0·10 mm a^{-1}, similar to pediment erosion rates in the Mojave Desert in the USA.

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